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WOOD AND OTHER RENEWABLE RESOURCES • CASE STUDY

Utilization of woody biomass in Singapore: technological options for carbonization and economic comparison with incineration

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Abstract
Background, aim and scope The interest in the use of biomass as a renewable energy resource has rapidly grown over the past few years. In Singapore, biomass resources are mostly from waste wood. This article presents a few technological options, namely carbonization, for the conversion of woody biomass into a solid fuel, charcoal.
Materials and methods In the first stage, a life cycle assessment (LCA) 'gate-to-gate' system was developed for a conventional carbonizer system, a modern carbonizer from Japan, and a proposed four-stage partial furnace carbonizer from Tunisia. The potential environmental impacts were generated for global warming potential, acidification, human toxicity and photochemical oxidant potential. Based on the first set of results, the second LCA investigation was carried out comparing the selected carbonizer from Japan and an existing incinerator in Singapore. The second LCA adopted a unique approach combining social costs of pollution with the economic factors of the two biomass conversion technologies.
Results The carbonizer from Japan resulted in approximately 85% less greenhouse gases than the conventional carbonization system and 54% less than the proposed four-stage carbonizer from Tunisia. In terms of acidification and human toxicity, the carbonizers from Japan and Tunisia display nearly similar results—both were considerably lower than the conventional carbonizer. For photochemical oxidant potential, very minimal emissions are generated from the four-stage carbonizer and nearly zero impact is realized for the carbonization technology from Japan.
Discussion From the first set of LCA results, the Japanese carbonizer is favored in terms of its environmental results. The highest environmental impacts from the conventional carbonizer were due to large and uncontrolled emissions of acidic gases, greenhouse gases (particularly CO_2 and CH_4), particulates, and non-methane volatile organic compounds from both fugitive sources and energy requirements. The second LCA addressed the performance of the carbonizer from Japan against an existing incinerator in terms of environmental as well as cost performances. This unique approach translated pollution emissions into monetary costs to highlight the impacts of social health.
Conclusions For the first LCA, the accumulated impacts from the Japanese carbonizer proved to display significantly lower environmental impacts, especially for global warming potential. The overall environmental performance of the four-stage carbonizer from Tunisia ranked slightly lower than the one from Japan and much higher than the conventional carbonizer. The second LCA results displayed a noteworthy improvement of 90% for human health from the modern Japanese carbonizer technology—when compared against conventional incinerators. Without considering health issues or social costs, the total value per ton of wood treated is nearly similar for both incinerator and carbonizer.
Recommendations and perspectives The interest in biomass as raw material for producing energy has emerged rapidly in many countries. However, careful analysis and comparison of technologies are necessary to ensure favorable

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environmental outcomes. A full life cycle study, along with costs and the impact of pollution on society, should be performed before any large-scale biomass conversion technology is implemented. LCA can be applied to quantify and verify the overall environmental performance of a particular technology of interest as well as further explore the proposed technology in terms of costs and social implications.

Keywords Air emissions · Biomass utilization · Carbonization · Gate-to-gate · Incineration · Social costs

1 Introduction

In recent years, public and political sensitivities to environmental issues and energy security have led to the promotion of indigenous renewable energy resources. Biomass is one of the renewable resources that could play a substantial role in offering sustainable and innovative solutions for providing new forms of power generation, heat, and energy feedstock. Biomass may be defined as any renewable source of fixed carbon. As a small industrialized nation with limited land for agriculture, the sources of biomass in Singapore are solid wastes and industrial residues. The types of biomass available in Singapore are from household and industrial waste streams. They are (NEA 2007):

- Wastepaper and cardboard (1,116,300 tons/year)
- Food residue (542,700 tons/year)
- Timber and scrap wood (223,700 tons/year)
- Horticultural (also from tree felling and pruning) (231,000 tons/year)

Clean and environmentally friendly methods for woody biomass waste utilization are sought as part of the country's commitment for achieving sustainable and environmental practices. The main sources of biomass are waste wood from industry together with the felling of trees along the roads and sidewalks in Singapore's 'green city state'.

In the first part of this paper, three carbonizer technologies will be compared. Charcoal, a solid carbon residue, can be produced from the carbonization of carbonaceous raw materials such as woody biomass. The fabrication of briquettes from raw materials may be processed either by an integral part of a charcoal-producing facility or as an independent operation. The wood-to-charcoal conversion process, known simply as carbonization, begins with crushed wood as the starting material. Before the wood passes through the furnace, it is passed through a large drum dryer which removes its moisture.

To convert a carbon-containing substance to carbon, the carbonizing process starts by heating up woody biomass under limited or non-oxygen conditions. This is also known as partial combustion. The carbonization process is conducted at temperatures ranging between 350 and 700°C. Controlled residence times, usually set at about 40 to 60 min, and carbonization temperatures are the most critical parameters in the entire process (Schenkel et al. 1999).

At high temperatures during the process, polyvinyl chlorides and the like will not react with oxygen because the oxygen content is less than 1%. Well-controlled carbonizers are able to minimize or eliminate dioxin emissions. The optimization of the carbonization process consists in maximizing the charcoal yield for a given quality of charcoals measured by the volatiles or the fixed carbon content. The optimization of both the quantity and quality of the final charcoal product evolves in a contradictory way. High-quality charcoals with a high content of fixed carbon can only be obtained at a high temperature, which means a poor mass yield (Khoo and Tan 2005). This study aims to clarify the environmental performance of three different carbonization technologies: (1) conventional system, (2) modern carbonizer from Japan, and (3) four-stage partial furnace carbonizer from Tunisia.

More detailed technical descriptions of the conventional charcoal production process can be found from various reports (Moscowitz 1978; Walter 1985; Bhattacharya et al. 1990). As for the Japanese carbonizer, details of the process can be obtained from Actree Corp (2005) in Japan. Technical and engineering specifications of the wood carbonization equipped with four partial combustion furnaces can be found in Halouani and Farhat (2003).

2 Materials and methods

2.1 LCA of biomass conversion

Life cycle assessment (LCA) has become a worldwide environmental management tool with the advent of the ISO 14040 international standards (Tan and Khoo 2006). LCA provides the data to allow informed environmental management. The generated life cycle impact assessment (LCIA) results can provide information for decision making at all levels—technical, administrative, and top management. Updates of new information are possible to be included in any LCA model (Tan 2003). The LCA framework consists of the following phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

2.1.1 First stage of LCA: wood-to-charcoal

In the first stage LCA investigation, the total environmental impacts of the three carbonizers are compared. In the LCA

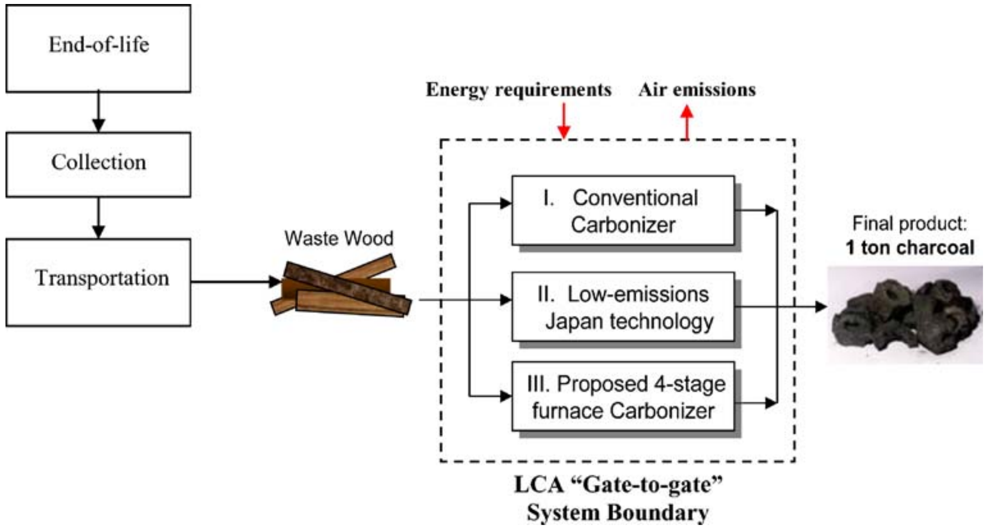

Fig. 1 System boundary for first stage of investigation

model, the emissions and energy demands for collection and transportation of waste wood are assumed to be similar for all three cases. Therefore, these two stages are not necessary to be included.

The system boundary is a 'gate-to-gate' model for comparing the carbonizers, starting from waste wood and ending with finished product (charcoal). The functional unit is selected as *1 ton charcoal* product. This is shown in Fig. 1.

The main emissions generated from the carbonization systems are oxides of sulfur and nitrogen (SO_x and NO_x), non-methane volatile organic compounds (NMVOC), particulates (PM), and greenhouse gases: carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and nitrous oxide (N_2O). The sources of the air pollution are from both direct (fugitive emissions) and energy usage (power generation plants).

2.1.2 Life cycle inventory

The air emission data for all three carbonizers were compiled from companies in Japan (Actree Corp 2005) as well as from various sources and reports (Moscowitz 1978; Walter 1985; Bhattacharya et al. 1990; Halouani and Farhat 2003). The inventory results, which are displayed in Table 1, are expressed as total air pollutants per functional unit.

2.1.3 Life cycle impact assessment

According to the new ISO 14044 standards (Finkbeiner et al. 2006), LCIA includes several steps from the inventory to the interpretation: (1) assignment of LCI results (classification); (2) calculation of category indicator results (characterization); (3) normalization; and finally (4) weighting. The last two stages are optional. In this case study, it was decided that normalization and weighting of results are unnecessary.

3 Impact assessment results

The EDIP 1997 impact assessment method is used for calculating the potential environmental impacts of: global warming potential (kg CO_2-eq); acidification (kg SO_2-eq); human toxicity to air (m^3 air); and finally photochemical oxidation (kg ethane-eq). The results are in Fig. 2 (global warming potential), Fig. 3 (acidification), Fig. 4 (human toxicity to air), and Fig. 5 (photochemical oxidation).

For global warming potential (refer to Fig. 2), the carbonizer from Japan resulted in approximately 85% less greenhouse gases than the conventional carbonization system and 54% less than the proposed four-stage carbonizer from Tunisia. As the issue of global warming becomes increasingly important in today's society, this advantage serves as a benefit for both environmental protection as

Table 1 Inventory results for emissions to air from processes and energy requirements based on 1 ton charcoal production

Total air emissions (kg)	Conventional carbonizer technology	Japan carbonization technology	Carbonizer with four partial combustion furnaces
SO_x	12.50	4.78	5.82
NO_x	11.60	3.19	1.93
CO	10.89	0.243	21.74
CO_2	498.96	324.80	576.99
CH_4	49.90	0.0047	3.57
N_2O	n.a.	0.0018	0.0023
PM	166.00	0.11	0.090
NMVOC	122.47	0.013	0.017

n.a. not available

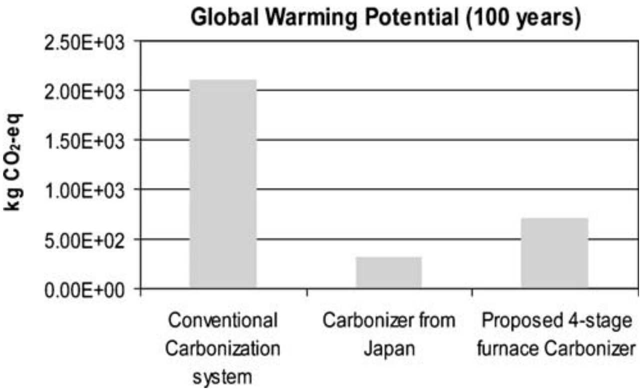

Fig. 2 Global warming potential results

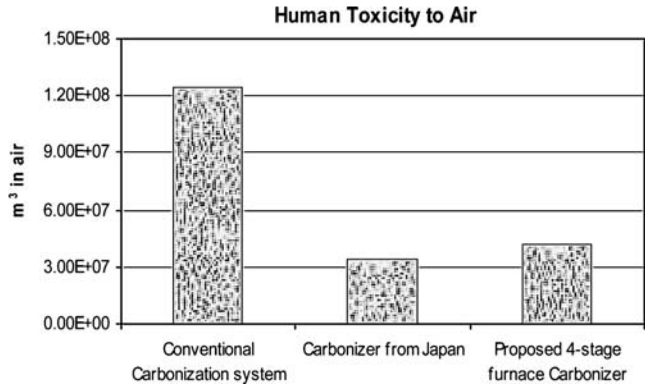

Fig. 4 Human toxicity to air results

well as the potential for renewable energy utilization. As for acidification (refer to Fig. 3), the results for both technologies from Japan and Tunisia are nearly similar. In terms of acidic gas emissions, the conventional system contributed nearly double to the impact category as compared with the other two.

Figure 4 displays that the human toxicity impacts for the technology from Japan resulted in 73% less than that of the conventional system and 20% less than that of the proposed four-stage carbonizer. For the last impact category, photochemical oxidant potential, Fig. 5 displays that very minimal emissions are generated from the four-stage carbonizer and nearly zero impact is realized for the carbonization technology from Japan.

Based on the overall performance, the Japanese carbonizer is favored in terms of its relatively good environmental performance as compared with the other two. Next is the four-stage partial combustion technology from Tunisia. The highest environmental impacts from the conventional carbonizer were due to large uncontrolled emissions of acidic gases, greenhouse gases (especially CO_2 and CH_4), PM, and NMVOCs from both fugitive sources and energy requirements.

The next issue to be addressed is the performance of the selected carbonizer against an existing incinerator in terms of reduced pollution and the associated costs.

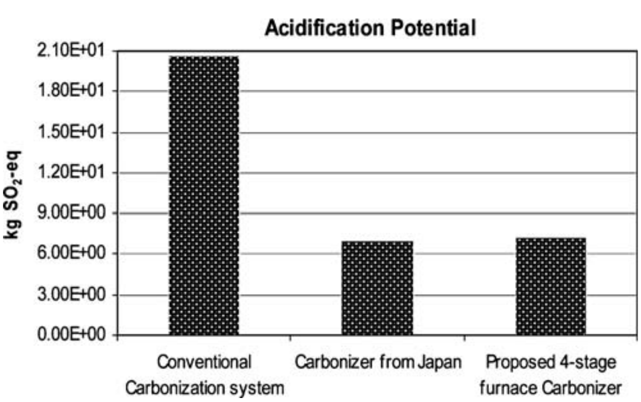

Fig. 3 Acidification results

4 Next stage: carbonization vs. incineration

Based on the first set of results, the carbonization technology from Japan is selected to be compared against the incineration of wood wastes. Due to lack of territory for landfills in Singapore, approximately 90% of waste materials that are not reused or recycled are sent to incinerators. Incinerators are employed to recover heat from its boilers, after which the heat is used to generate electricity via steam turbo-generators. Of all the pollutants arising from the incineration of wastes, those released to the atmosphere have received most attention from environmental organizations and policy makers (Hester and Harrison 2002). Stringent emission limits must be in place and all modern incinerators must be equipped with pollution control systems to minimize these harmful emissions. These pollution control technologies are capable of removing up to 90% of SO_x and NO_x emissions as well as 95% of the toxic metal gases (Tan and Khoo 2006).

4.1 Air pollution and damages to health

A consensus has emerged among public health experts that air pollution, even at ambient levels, is associated with a variety of health problems, especially respiratory diseases (Hester and Harrison 2002). Various clinical studies that aim to establish

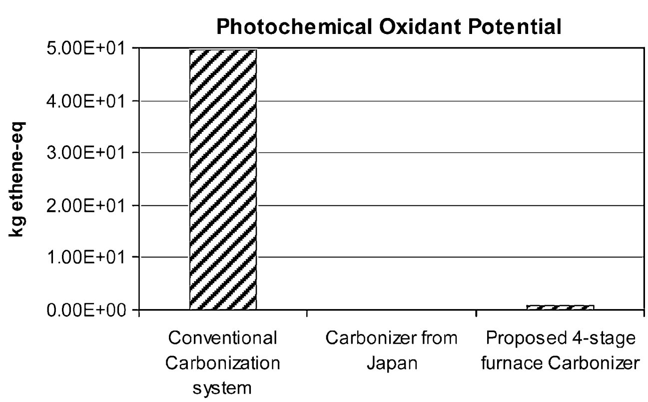

Fig. 5 Photochemical oxidation potential results

Table 2 Incineration and carbonization emissions

Main air emissions (kg/ton waste wood)	Incinerator	Japan modern carbonization technology
SO_x	0.12	0.65
NO_x	1.01	0.43
CO	0.18	0.033
CO_2	1,280	43.89
Dioxins/furan	6.89E−08	0
PM	0.021	0.015

the relationship between air pollution and damages to human health have been carried out (Hofstetter 1999).

Investigations carried out by health experts and scientists are done to connect the level of concentration and dispersion of air pollutants with crude mortality rates as well as the monetary values of such mortality and morbidity levels (Spadaro and Rabl 2002). As far as data and models are available, the correlation between air pollutants and damages to health has been generated for (Quah and Boon 2003; Khoo et al. 2006): (1) specific emissions (kilogram pollutants of SO_2, NO_2, and CO), (2) impact pathways (inhalation, incidental digestion, etc.), (3) calculation of damages using dose–response function (e.g., number of asthma attacks due to the air particles), and (4) monetary valuation of the damage caused.

For LCA studies, a cause–damage relationship can be determined by calculating the emissions from the reference flow of a selected functional unit (Khoo et al. 2006).

4.2 Integrating LCA with social cost factors

In this unique approach, the social costs factors, along with other cost considerations, will be integrated with LCA. The benefits of this kind of approach have been demonstrated by Khoo et al.(2006). It can be used for the following applications:

- for measuring both financial and environmental performance goals
- decision making for investment in environmental improvement objectives
- the social costs of pollution can be totaled and expressed in monetary units
- the final results may be displayed as a breakdown of expenses

The main air emissions that are known to cause health problems are SO_x, NO_x, CO, CO_2, dioxins/furans, and PM (Hester and Harrison 2002; Hofstetter 1999). Based on the new functional unit of 1 ton of waste wood treated, the inventory results are displayed in Table 2. The data displayed is inclusive of both fugitive emissions and those from energy use.

The social costs per pollutants for various substances are extracted from Spadaro and Rabl (2002) and are compiled in Table 3. These social costs are extracted from the authors based on European studies and translated into Singapore dollars or SGD. These cost factors are used based on Singapore's demographic similarities with many parts of Western Europe such as high population density—and therefore high importance on human health—and advanced commercial cities.

The next round of LCA investigation is carried out for the following cost parameters: (1) energy input (kerosene/natural gas); (2) operating costs per ton of treated waste (wood); (3) electricity requirement; (4) value of charcoal (treated as negative cost); and finally (5) social costs of pollution.

The LCA model detailing the energy and material flows for costing is shown in Fig. 6.

It must be brought to attention that, while the first stage of investigation focused on the production of charcoal (which was selected as the functional unit for the first LCA), the second stage of investigation takes on a different approach. The second LCA system was modeled for generating the total costs of two entirely different technologies which yield two different products, charcoal and electricity. In this case, the selected functional unit is 1 ton of wood waste treated. The associated amounts of energy, emissions, and products are converted into monetary units to enable a common measure—costs—that can be used as grounds for comparison, based on the *fiscal value* of each product. The new inventory for the second LCA system is compiled in Table 4.

5 Costs results and discussions

The breakdown of costs for energy usage, process operations, pollution, and products (indicated as negative costs) is shown below in Fig. 7. The process or operating cost of the carbonizer is 30% more than that of the incinerator, but the social cost of pollution is approximately 90% less.

Lately, the intensification of waste treatment processes, especially incineration, over the past few decades has contributed considerably to a rapid drop in air quality in many countries. Specific chemicals discharged from incin-

Table 3 Social costs of air pollution

Estimated social and economic cost of emissions						
$/kg	CO	CO_2	SO_x	NO_x	PM	Dioxins/furans
	0.004	0.057	0.58	2.92	30.0	3.6E+07

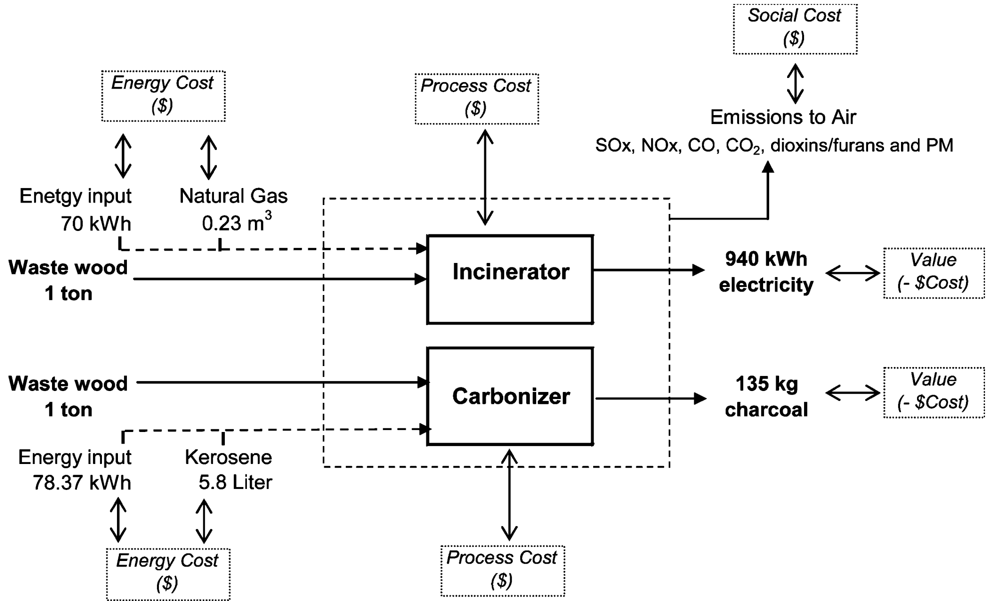

Fig. 6 Costs associated with energy use, pollution (social costs) and final value of product

erators along with harmful air emissions can cause severe consequences for human health and the environment (Astrup et al. 2005).

The major social costs arising from the incinerator are emissions of dioxins and furans. Such emissions are classified as some of the most toxic chemicals known to medical science and are priced at an extremely high amount, that is, SGD3.6E+07 per kilogram (Spadaro and Rabl 2002). Known as a cancer hazard to humans, dioxins in the environment from waste-burning incinerators have become a growing concern in many countries. The next major pollutant from incinerators is PM, priced at SGD30.0 per kilogram (Spadaro and Rabl 2002). Clinical studies have shown that long-term ambient exposure to PM concentrations can lead to a marked reduction in life expectancy, primarily due to increased cardiopulmonary and lung cancer mortality (Hester and Harrison 2002; Hofstetter 1999; Spadaro and Rabl 2002; Quah and Boon 2003).

In terms of greenhouse emissions, the levels of CO_2 are significantly higher from the incinerator as compared to the carbonizer from Japan. Although the social costs of CO_2 is much less than that of dioxins/furans and PM in terms of kilogram pollutant, the accumulated amount most likely added to the high social costs level depicted in Fig. 7.

The difference between the worth of the two products is 35% more for the carbonizer, based on per ton of wood treated. However, it must be highlighted that the emissions of VOCs or any other gases released during the use of charcoal have not been included in the system boundary. This is one of the limitations of the 'gate-to-gate' system boundary modeled for two different products. Without considering social costs, the total value per ton of wood treated is nearly similar for both systems.

Table 4 Cost and energy for the two technologies (per ton of wood treated)

Costs and operating conditions	Waste treatment technology	
	Incinerator (Singapore)	Carbonizer (Japan)
Type of material processed	Waste wood	Waste wood
Main product	Electricity (940 kWh/ton)	Charcoal (135 kg/ton)
Value of product	S$0.12/kWh	S$1.29/kg
Operating costs in SGD/ton	70	100
Electricity requirements (kWh/ton wood)	70	78.37
Other energy requirements	Natural gas (0.23 m^3/ton)	Kerosene (5.8 l/ton)
Other costs	S$0.7 per cubic meter natural gas	S$0.53 per liter kerosene

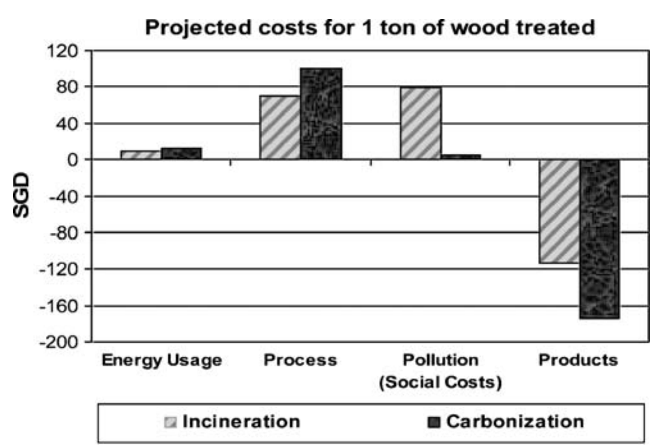

Fig. 7 Breakdown of costs for incinerator and carbonizer

6 Conclusions

The conversion of biomass to fuels and bio-products will continue to attract attention from both researchers and industry. Modern technology, material science, and bio-process engineering have matured and allowed for a wide range of bio-based products such as biodegradable plastics, bio-composites, bulk chemicals, and bio-fuels.

An LCA 'gate-to-gate' system was developed for a conventional carbonizer system, a modern carbonizer from Japan, and a proposed four-stage partial furnace carbonizer from Tunisia. The potential environmental impacts were generated for global warming potential, acidification, human toxicity and photochemical oxidant potential. The final weighted scores (total accumulated impacts) showed that the carbonizer from Japan generated 75% less air pollution than the wood-to-charcoal conversion system. The four-stage furnace resulted in 68% lower impacts than the conventional carbonization system.

The next stage of the LCA investigation was carried out to understand the environmental as well as social and cost performance of two wood treatment technologies—one utilizing the carbonizer from Japan and the other an existing incinerator in Singapore. Incineration has remained a major option for the disposal of waste; advantageous because it greatly reduces the space requirements for landfills, yet highly controversial because of perceived health risks from air emissions, particularly dioxins (Tan and Khoo 2006).

The monetary cost of air pollution damages to health have been projected by clinical studies employing combinations of 'impact pathway' (the exposure pathway or transport route from pollutants to humans) and 'dose–response relationships', that is, the modeling of the amount of pollutant that a human has been exposed to and the related health consequences. The second set of results shows a significant improvement (90%) for human health concerns by employing the modern carbonizer technology.

Without considering social costs, the total value per ton of wood treated is nearly similar for both incinerator and carbonizer.

7 Recommendations and perspectives

In Singapore, biomass is viewed as a potentially important renewable resource, with the potential to meet the demand for more environmentally benign feedstocks in industry as well as for the production of fuels and electricity. Careful selection of technologies is necessary before implementation of any large-scale systems for biomass utilization. A life cycle study, along with costs and the impact of pollution on society, should be performed before any large-scale biomass conversion technology is implemented. A full evaluation of the potential environmental impacts of biomass-to-bioenergy conversion systems is necessary to ensure that the desired environmental outcomes are achieved. It is also suggested that further analysis of the selected technology can be carried out to assess costs from energy usage as well as social costs of health impacts from air pollution. In this kind of unique LCA approach, the amounts of energy, emissions, and materials are translated into monetary units to enable a common measure, the total costs of the system.

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